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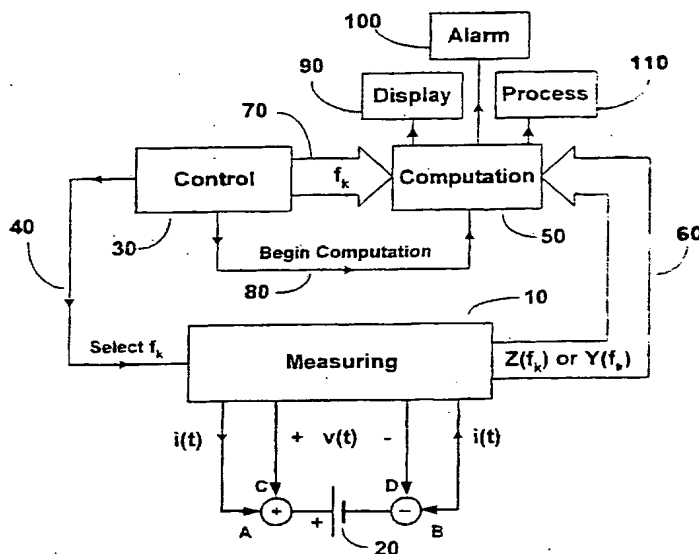
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(54) Title: **METHOD AND APPARATUS FOR ELECTRONICALLY EVALUATING THE INTERNAL TEMPERATURE OF AN  
ELECTROCHEMICAL CELL OR BATTERY**



(57) **Abstract:** A testing device applies time-varying electrical excitation to a cell or battery (20) and senses the resulting time-varying electrical response. Computation circuitry (50) within the device uses voltage and current signals derived from the excitation and response signals as inputs and computes values of elements of an equivalent circuit representation of the cell or battery (20). The internal temperature of the cell or battery (20) is calculated from the value of the time constant of a particular parallel G-C subcircuit of the equivalent circuit. The battery's (20) internal temperature is then either displayed to the user, used to apply appropriate temperature corrections to other computed quantities, used to detect thermal runaway, and/or used to control an external process such as charging of the battery (20).

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METHOD AND APPARATUS FOR ELECTRONICALLY  
EVALUATING THE INTERNAL TEMPERATURE OF AN  
ELECTROCHEMICAL CELL OR BATTERY

BACKGROUND OF THE INVENTION

5           The present invention relates to testing of storage batteries. More specifically, the invention relates to measuring temperature of an electrochemical cell or battery.

10           When testing or evaluating the performance of cells and batteries, it is desirable to accurately know battery temperature in order to apply appropriate temperature corrections to the measured results. For example Champlin, in U.S. Patent 3,909,708, describes setting a dial on the tester to the battery's  
15   temperature in order to cause the measured dynamic conductance to comport with that of a battery at room temperature. However, exactly how this battery temperature information is to be obtained is not discussed. Others employ a very rough correction by  
20   instructing the user to push a button when the ambient temperature is, e.g., "below 0° C". Marino et al., in U.S. Patent 4,423,378 refer to a battery temperature "probe" whose output is inputted to a microprocessor for the purpose of correcting load-test results.  
25   Similar temperature probes are described by Alber et al. in U.S. Patent 4,707,795. Other workers have attached thermistors to test clips so that they would be in thermal contact with a battery terminal, or have

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placed them in thermal contact with the battery's case. Even infrared techniques have been used to determine battery case temperature.

All of these prior art techniques have measured either the battery's ambient temperature or its external case temperature. Unfortunately however, these quantities can be very different from the actual internal temperature of the battery -- the truly desired quantity. These temperature differences come about from localized internal heating caused by currents flowing through the battery, from the large thermal mass of the battery, and from the poor thermal contact between the battery and its environment. For example, an automobile engine compartment will warm up rapidly with the engine running. If the battery is cold, however, its internal temperature will remain low for a very long period of time.

#### SUMMARY OF THE INVENTION

A testing device applies time-varying electrical excitation to a cell or battery and senses the resulting time-varying electrical response. Computation circuitry within the device uses voltage and current signals derived from the excitation and response signals as inputs and computes values of elements of an equivalent circuit representation of the cell or battery. The internal temperature of the cell or battery is calculated from the value of the time constant of a particular parallel G-C subcircuit of the equivalent circuit. In various aspects, the battery's

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internal temperature is then displayed to the user, used to apply appropriate temperature corrections to other computed quantities, used to detect thermal runaway, and/or used to control an external process  
5 such as charging of the battery.

#### BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block diagram of a device for measuring the internal temperature of an electrochemical cell or battery according to the  
10 present invention.

FIG. 2 depicts a six-element small signal equivalent circuit representation of a particular automotive storage battery.

FIG. 3 is a plot of the variation of the  
15 three subcircuit time-constants defined in FIG. 2 as functions of the charge removed from the battery.

FIG. 4 is a plot of measured and theoretical values of time constant  $\tau_3$  defined in FIG. 2 as functions of the internal temperature of the battery.

20 FIG. 5 is a plot of the inverse of the relationship plotted in FIG. 4.

FIG. 6 is a circuit representation of the parallel G3-C3 subcircuit showing its admittance Y3.

#### DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

25 Clearly, a method and apparatus for electronically determining the true internal temperature of a cell/battery would be of great value. The present invention addresses this need. It is based upon teachings disclosed in pending

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A very important application of the method taught herein is in the detection of "thermal runaway" - a phenomenon in which the internal temperature of a battery undergoing charging rises catastrophically (see, e.g., McShane et al., U.S. Patent 5,574,355). Using the technique disclosed below, a runaway condition can be quickly detected by a precipitous internal temperature rise, which, in turn could be used to shut off the charger or reduce its charging voltage.

Figure 1 discloses a block diagram of apparatus for evaluating a battery's internal temperature according to the present invention. Apparatus of this type is fully disclosed in pending U.S. Patent Application Ser. No. 09/152,219, filed September 11, 1998 and entitled "METHOD AND APPARATUS FOR MEASURING COMPLEX IMPEDANCE OF CELLS AND BATTERIES" and pending U.S. Patent Application 09/151,324, filed September 11, 1998, entitled "METHOD AND APPARATUS FOR DETERMINING BATTERY PROPERTIES FROM COMPLEX IMPEDANCE ADMITTANCE" which are incorporated herein by reference. Measuring circuitry 10 electrically couples to cell/battery 20 by means of current-carrying contacts A and B and voltage-sensing contacts C and D. Measuring circuitry 10 passes a periodic time-varying current  $i(t)$  through contacts A and B and senses a periodic time-varying voltage  $v(t)$  across contacts C and D. By appropriately processing and combining  $i(t)$  and  $v(t)$ , measuring circuitry 10 determines real and

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imaginary parts of a complex parameter, either impedance  $Z$  or admittance  $Y$ , at a measuring frequency  $f_k$ ; where  $f_k$  is a discrete frequency contained in the periodic waveforms of both  $i(t)$  and  $v(t)$ .

5           Control circuitry 30 couples to measuring circuitry 10 via command path 40 and commands measuring circuitry 10 to determine the complex parameter of cell/battery 20 at each one of  $n$  discrete measuring frequencies, where  $n$  is an integer  
10           number. This action defines  $3n$  experimental quantities: the values of the  $n$  measuring frequencies and the values of the  $n$  imaginary parts and  $n$  real parts of the complex parameter at the  $n$  measuring frequencies.

15           Computation circuitry 50 couples to measuring circuitry 10 and to control circuitry 30 via data paths 60 and 70, respectively, and accepts the  $2n$  experimental values from measuring circuitry 10 and the values of the  $n$  measuring frequencies from  
20           control circuitry 30. Upon a "Begin Computation" command from control circuitry 30 via command path 80, computation circuitry 50 uses algorithms disclosed in U. S. Patent Application 09/151,324 to combine these  $3n$  quantities numerically to evaluate  
25            $2n$  elements of an equivalent circuit representation of the cell/ battery. Computation circuitry 50 then calculates the internal temperature of the cell/battery from values of particular elements of this circuit representation. Finally, computation

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circuitry 50 outputs the computed result to the user on display 90 and/or uses the result to activate an alarm 100 or to control a process 110 such as a battery charger.

5 In practice, a microprocessor or microcontroller running an appropriate software program can perform the functions of both control circuitry 30 and computation circuitry 50.

Figure 2 discloses a six-element equivalent  
10 circuit representation of a typical automotive storage battery. This circuit representation was evaluated using apparatus of the type disclosed in FIG 1 with  $n=3$  by employing algorithms disclosed in U.S. Patent Application 09/151,324. The three  
15 measurement frequencies were 5 Hz, 70 Hz, and 1000 Hz. One notes that the  $n=3$  equivalent circuit comprises three subcircuits:

- A series G1-L1 subcircuit.
- A parallel G2-C2 subcircuit.
- 20 • A parallel G3-C3 subcircuit.

One notes further that the three subcircuits are characterized by having very different time constants. The shortest time constant,  
 $\tau_1 = L1 \cdot G1 = 93.5\mu S$ , belongs to the series G1-L1  
25 subcircuit. The next longest time constant,  
 $\tau_2 = C2/G2 = 2.22mS$ , belongs to the parallel G2-C2 subcircuit; and the longest time-constant,  
 $\tau_3 = C3/G3 = 41.6mS$ , belongs to the parallel G3-C3

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subcircuit. Accordingly, the three subcircuits represent quite different physical processes and can be differentiated from one another by their time constants.

5           Figure 3 is a logarithmic plot of the three time constants defined above as functions of charge (ampere-hours) removed from the battery. One notes that the three time constants remain widely separated as charge is removed, and that the longest of the  
10 three,  $\tau_3$ , is nearly independent of state-of-charge. This result is important to the present invention.

          Figure 4 discloses the observed variation of time constant  $\tau_3 = C3/G3$  with internal battery temperature. One sees that  $\tau_3$  varies inversely with  
15 temperature. This variation is consistent with a theoretical model that associates the G3-C3 subcircuit with a linearized, small-signal, representation of the nonlinear electrochemical reaction occurring at the negative plates. For such a model, the RC product  
20  $\tau_3 = C3/G3$  represents the reaction time for the process and therefore varies inversely with temperature. By empirically establishing this relationship between  $\tau_3$  and T, one can actually utilize measurements of  $\tau_3$  to determine the battery's internal temperature, T.

25           Figure 4 shows experimental points compared with a theoretical  $\tau_3(T_c)$  relationship. Note that the steepest slope, and hence the most accurate temperature determination, occurs in the most interesting region



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between  $-20^{\circ}\text{C}$  and  $+20^{\circ}\text{C}$ . The theoretical curve disclosed in FIG. 4 is a plot of the following equation:

$$\tau_3(T_c) = K_3 + \frac{1}{\frac{1}{K_2} + \frac{1}{K_1 \exp\{qV_0/k(T_c + 273^{\circ})\}}} \quad (1)$$

where  $\tau_3$  is the time constant measured in milliseconds and  $T_c$  is the internal temperature measured in degrees Celsius. Physical parameters introduced in this equation are:

$k = 1.38 \times 10^{-23} \text{ Joules}^{\circ}\text{K}$  (Boltzman's Constant)

$q = 1.6 \times 10^{-19} \text{ Coulombs}$  (electronic charge)

$V_0 = 0.85 \text{ eV}$  (activation energy)

The three constants  $K_1$ ,  $K_2$ , and  $K_3$  were empirically determined to be

$$K_1 = 2.0 \times 10^{-14}$$

$$K_2 = 67.0 \text{ mS}$$

$$K_3 = 37.0 \text{ mS}$$

One notes excellent agreement between theory and experiment. Measurements show that  $\tau_3$  is virtually independent of battery size and state-of-charge (see FIG. 3). Thus, this empirical  $\tau_3(T_c)$  relationship plotted in FIG. 4 appears to be quite universal.

In order to determine internal temperature from time constant measurements, one must

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mathematically invert the above  $\tau_3(T_c)$  relationship to obtain a  $T_c(\tau_3)$  relationship. The result is:

$$T_c(\tau_3) = \frac{(qV_0/k)}{\ln \left\{ \frac{(K_2/K_1)(\tau_3 - K_3)}{(K_2 + K_3 - \tau_3)} \right\}} - 273^\circ \quad (2)$$

5

where the parameters and constants,  $q$ ,  $V_0$ ,  $k$ ,  $K_1$ ,  $K_2$ ,  $K_3$ , are the same as those introduced in the  $\tau_3(T_c)$  relationship.

The inverse theoretical  $T_c(\tau_3)$  curve is plotted in FIG. 5. By employing this relationship, one can readily determine the battery's true internal temperature from measurements of  $\tau_3$ . This important temperature information can then be used to apply accurate temperature corrections to other measured quantities, such as CCA, state-of-charge, and amp-hour capacity. It can also be used to detect a thermal runaway condition, and to control an external process such as a battery charger.

This completes the disclosure of my invention. Figures 6, however, will place the true nature of the invention in greater perspective. Figure 6 illustrates the G3-C3 subcircuit and shows that the complex admittance of this parallel subcircuit,  $Y3 = G3 + j\omega C3$ , explicitly contains the two quantities,  $G3$  and  $C3$ , necessary to determine the battery's internal temperature. Thus, my discussion above actually discloses a relationship existing between the

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real and imaginary parts of  $Y_3$  and the internal temperature of the battery. Although it is true that complex  $Z$  and complex  $Y$  are reciprocals of one another, no simple relationship exists between the real and imaginary parts of impedance  $Z_3$  and time constant  $\tau_3$ .  
5 Accordingly, the results of any ac measurement must be expressed in complex admittance form - not complex impedance form - in order to observe the important relationship that I have disclosed herein. How this  
10 complex admittance is obtained, however, is relatively unimportant.

Although my disclosure has relied upon particular apparatus and algorithms previously disclosed in U.S. Patent Applications Ser. No.  
15 09/152,219 and Ser. No. 09/151,324, other methods will be apparent to one skilled in the arts. For example, one can employ bridges or other types of apparatus to measure complex admittance (or its reciprocal, complex impedance). Furthermore, if accuracy is not a strict  
20 requirement, one can take advantage of the fact that the various time constants are widely separated from one another and simply assume that the subcircuits are not coupled. Within this approximation,  $C_2$  and  $C_3$  are treated as short circuits at frequencies near  
25  $f_{01} = 1/2\pi\tau_1$ ,  $L_1$  and  $C_3$  are treated as short circuits at frequencies near  $f_{02} = 1/2\pi\tau_2$ , and at frequencies near  $f_{03} = 1/2\pi\tau_3$ ,  $L_1$  is treated as a short circuit while  $C_2$  is treated as an open circuit. Thus, with some batteries,

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it is possible to obtain satisfactory results from a very simple analysis of measurements at two or three frequencies. With certain batteries, it is even possible to obtain useful approximations to  $Y^3$  from measurements of complex  $Y$  or  $Z = 1/Y$  obtained at a single, appropriately chosen, frequency. Workers skilled in the art will recognize that these and other variations may be made in form and detail without departing from the true spirit and scope of my invention.

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WHAT IS CLAIMED IS:

1. Apparatus for determining the internal temperature of an electrochemical cell or battery comprising:  
electrical excitation circuitry adapted to apply time-varying electrical excitation to said cell or battery;  
response sensing circuitry configured to sense time-varying electrical response of said cell or battery generated as a result of said time-varying electrical excitation; and  
computation circuitry responsive to said time-varying excitation and to said time-varying response and adapted to calculate the time constant of a particular parallel G-C subcircuit comprising part of an electrical circuit representation of said cell or battery, said time constant characterized by varying inversely with internal temperature, said computation circuitry further adapted to evaluate said internal temperature from the computed value of said time constant.

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2. The apparatus of claim 1 including a display device coupled to said computation circuitry and wherein the computation circuitry provides a temperature output on the display.

3. The apparatus of claim 1 wherein said computation circuitry couples to an external process device and said external process device is controlled by said computation circuitry in accordance with the computed value of said internal temperature.

4. The apparatus of claim 1 wherein said electrical circuit representation comprises at least three subcircuits having differing time constants and the time constant of said particular parallel subcircuit is longer than the time constants of at least two other subcircuits.

5. The apparatus of claim 1 wherein said electrical circuit representation comprises at least two subcircuits having different time constants and the time constant of said particular parallel subcircuit is longer than the time constant of at least one other subcircuit.

6. The apparatus of claim 1 including an output indicative of detect a thermal runaway condition, said condition characterized by a rapid rise in internal temperature while charging of the battery.

7. The apparatus of claim 6 including an alarm coupled to said computation circuitry and wherein the

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computation circuitry provides an alarm output in response to said thermal runaway condition.

8. The apparatus of claim 3 wherein said external process device is a battery charger.

9. A method for electronically evaluating the internal temperature an electrochemical cell or battery comprising:

applying time-varying electrical excitation to said cell or battery;

sensing time-varying electrical response to said electrical excitation;

evaluating the time constant of a particular parallel G-C subcircuit of an equivalent circuit representation of said cell or battery from said time-varying electrical excitation and said time-varying electrical response; and

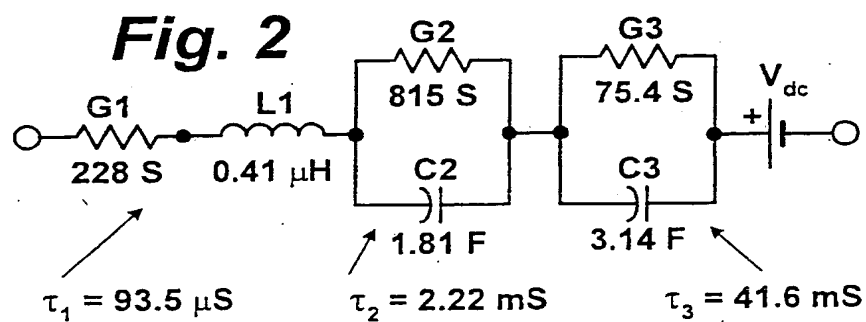
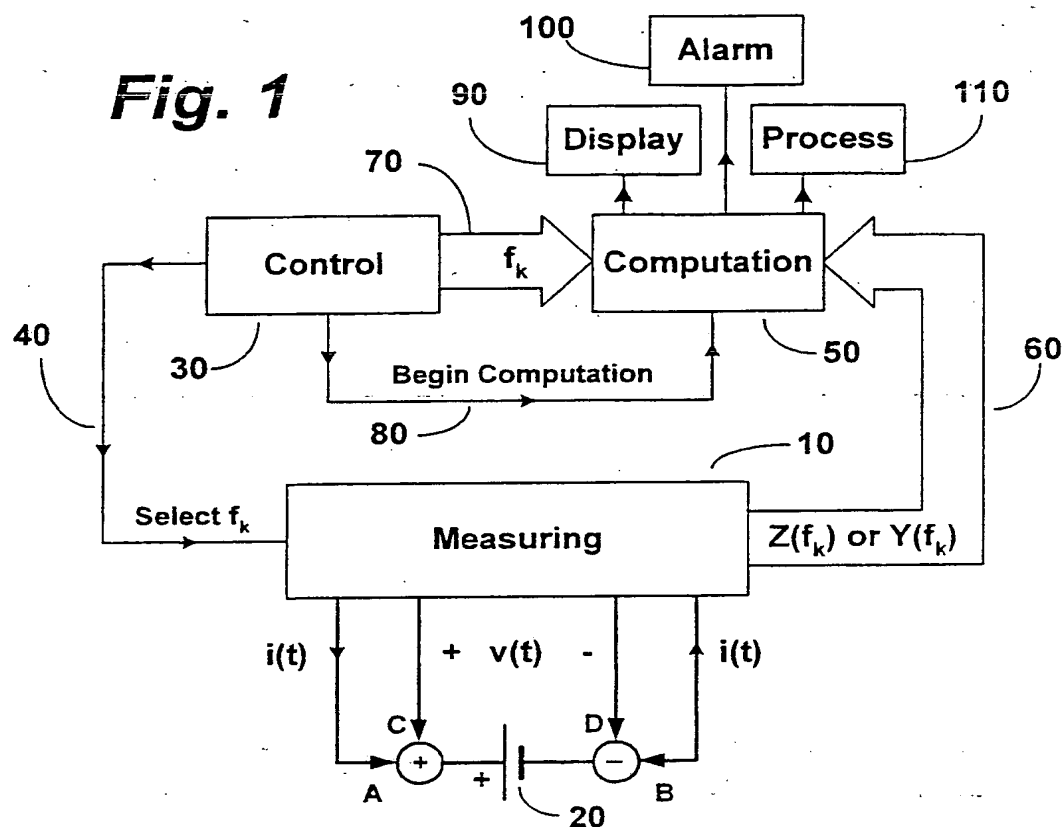
evaluating said internal temperature from the value of said time constant.

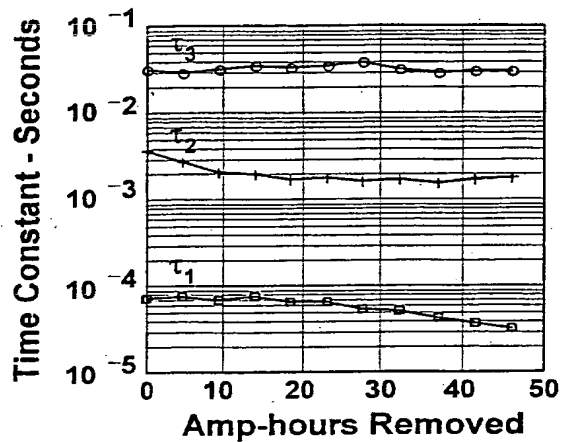
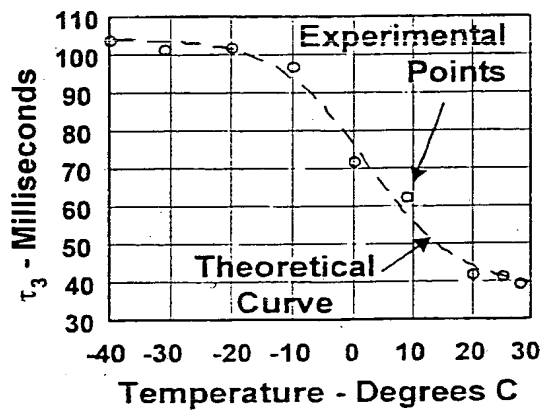
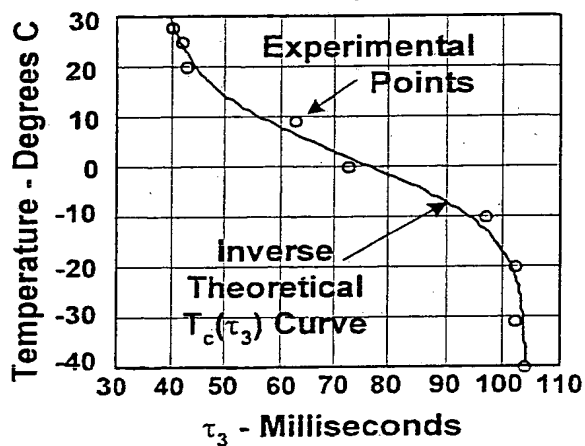
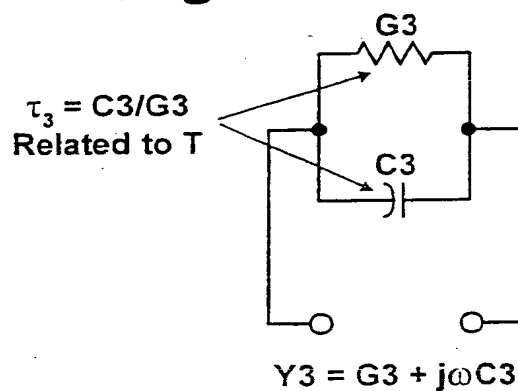
10. The method of claim 9 including the displaying said internal temperature to a user.

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11. The method of claim 9 including the controlling an external process device in accordance with said internal temperature.





**Fig. 3****Fig. 4****Fig. 5****Fig. 6**

# INTERNATIONAL SEARCH REPORT

Intern: al Application No  
PCT/US 00/24266

**A. CLASSIFICATION OF SUBJECT MATTER**  
IPC 7 G01R31/36

According to International Patent Classification (IPC) or to both national classification and IPC

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)  
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Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	PATENT ABSTRACTS OF JAPAN vol. 009, no. 085 (E-308), 13 April 1985 (1985-04-13) & JP 59 215674 A (SANYO DENKI KK), 5 December 1984 (1984-12-05) abstract	1,9
A	US 5 574 355 A (MC SHANE STEPHEN J ET AL) 12 November 1996 (1996-11-12) column 2, line 59 -column 5, line 6; figures 1,2	1,9

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

\* Special categories of cited documents :

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**INTERNATIONAL SEARCH REPORT**

Information on patent family members

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Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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US 5574355 A	12-11-1996	AU 5363496 A WO 9629773 A	08-10-1996 26-09-1996